

Reply to the comment

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The comment of M. Weiler *et al.* [1] raises a pertinent question about the origin of the electrical signal detected in our letter [2], reporting on the detection of the ac part of the spin-pumping current emitted during ferromagnetic resonance using the inverse spin Hall effect (ac-ISHE). The originality of our method was to induce a resonance in YIG|Pt at half the frequency using parametric excitation in the parallel geometry. Other attempts to measure the ac-ISHE have used a balanced circuit [3], spin rectification effects [4] or phase detection [5]. M. Weiler *et al.* point out to an inconsistency in the interpretation of our data: if indeed the uniform mode of our YIG would be excited, then the produced ferromagnetic inductive (FMI) voltage should have dominated over the ac-ISHE voltage and it should have lead to the same signal amplitude in both YIG|Pt and YIG|Al. In ref. [2], we report a signal in YIG|Pt that is about an order of magnitude smaller than the predicted FMI-voltage and the signal vanishes in the case of YIG|Al, where only the FMI-voltage should dominate.

Because we missed the estimation of the expected FMI contribution, we have revisited exhaustively [6] our measurement of the ratio, ρ , between the signal measured in the YIG|Pt and YIG|NM, where NM is a normal metal suppressing the ISHE. We present in FIG.1 two sets of measurements performed near the onset of the parametric excitation. We first show in panel (b) and (c), a comparison of the signal measured in YIG|Pt_{7nm} and in YIG|Pt_{7nm}|Al_{50nm} [7]. The two sets are performed at the same YIG location, ensuring that the parametric threshold is unchanged. Although increasing the NM thickness reduces the impedance of the circuit, this should enhance the FMI-part of the signal. This method thus yields an under-estimation of the ratio $\rho = |V_{\text{ISHE}} + V_{\text{FMI}}|/|V_{\text{FMI}}|$. Comparing the two samples, we find that the ratio ρ is larger than 5 when $P \leq 24$ dBm. The disappearance of the signal above 3 GHz is due to the fact that the stripline becomes there inefficient to pump parametrically the YIG. In order to check the influence of the impedance match, we have repeated the measurement in another YIG sample covered by three electronically connected slabs of respectively Pt_{7nm}, Al_{15nm} and Pt_{7nm}. Displacing the antenna laterally above each slab allows

to selectively excite the 3 different regions using the same impedance circuit (see FIG1 (d-f)). Although spatial variation of the YIG quality leads to error bars in the estimation of ρ , the 3 sets of measurements confirm that $\rho > 1$ at the settings used in ref. [2]. We also observe that this result is specific to excitation near the parametric threshold: at much larger power the ratio ρ decreases and eventually reaches 1.

Although, the large measured value of ρ confirms *experimentally* that indeed the ac-ISHE has been detected in ref. [2], we need to reconcile this result with the prediction [1] of the dominance of the FMI-voltage ($\rho = 1$). We note that $\rho - 1 \propto \langle \dot{M}_y \rangle / \langle \dot{M}_x \rangle$, where the over-dot denotes the time derivative and the chevron bracket indicates the spatial average (see FIG.1(a) for axes orientation). Therefore standing spin-waves (SW) excited along the YIG film thickness direction can significantly decrease the value of the FMI-voltage, while leaving the ac-ISHE voltage unchanged. Moreover, parametric excitation is known to be efficient at exciting spatially inhomogeneous SW [8–10]. Usually, the first magnons to go unstable are the $\pi/2$ -magnons ($k \perp M$) [8]. While we could determine experimentally that the excited SW are inhomogeneous in the $x - z$ plane [11], we could not find an unambiguous way to demonstrate that they are also inhomogeneous along y in our 200 nm thick YIG. This thus leaves us with a plausible explanation of the discrepancy but without a direct proof that this is what indeed occurs.

In summary, we confirm that close to the threshold the ratio ρ is larger than 1, suggesting that the signal is indeed dominated by the ac-ISHE as reported in our paper [2]. Nevertheless, the fact that uncharacterized spatially inhomogeneous SW are excited prevents a quantitative analysis of the measured signal.

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- [1] M. Weiler, H. T. Nembach, J. M. Shaw, and T. J. Silva, ArXiv e-prints (Jan. 2014), arXiv:1401.6407 [cond-mat.mtrl-sci]
[2] C. Hahn, G. de Loubens, M. Viret, O. Klein,

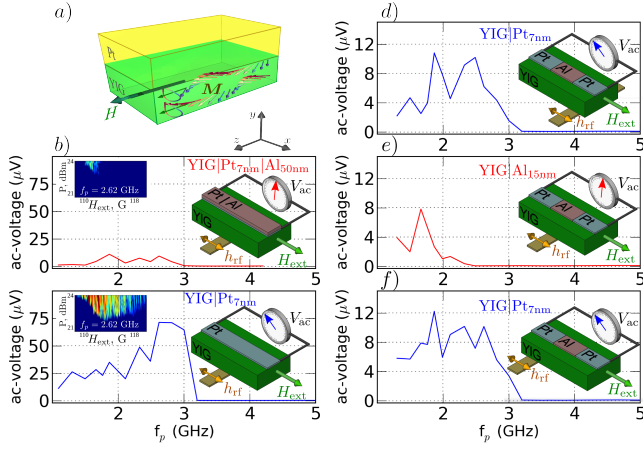


FIG. 1. (Color online) (a) Measurement of the ac-voltage (V_{ac}) produced by spin-waves excited parametrically. (b) and (c) are a comparative study of YIG|Pt_{7nm}|Al_{50nm} and YIG|Pt_{7nm} where the same YIG location is excited. V_{ac} as function of power (P) and bias magnetic field (H_{ext}), at constant pumping frequency (f_p), is shown in the insert. From there, the maximum V_{ac} for $P \leq 24$ dBm is extracted and plotted as function of f_p . Same measurement done on a slab covered successively by Pt_{7nm}(d) / Al_{15nm}(e) / Pt_{7nm}(f). Displacing the microwave antenna underneath the YIG allows to excite successively the Pt and Al using the same impedance circuit.

- V. V. Naletov, and J. Ben Youssef, Phys. Rev. Lett. **111**, 217204 (Nov 2013), <http://link.aps.org/doi/10.1103/PhysRevLett.111.217204>
- [3] D. Wei, M. Obstbaum, C. Back, and G. Woltersdorf, ArXiv e-prints(Jul. 2013), arXiv:1307.2961 [cond-mat.mes-hall]
- [4] P. Hyde, L. Bai, D. M. J. Kumar, B. W. Southern, S. Y. Huang, B. F. Miao, C. L. Chien, and C.-M. Hu, ArXiv e-prints(Oct. 2013), arXiv:1310.4840 [cond-mat.mtrl-sci]
- [5] M. Weiler, J. M. Shaw, H. T. Nembach, and T. J. Silva, ArXiv e-prints(Jan. 2014), arXiv:1401.6469 [cond-mat.mes-hall]
- [6] We have checked that the experimental results presented herein are similar on different geometries, using different NM patterns (single slab or double coplanar loop), flipping sample side, detecting the signal at $f/2$ or $3f/2$, as well as changing the YIG thickness.
- [7] Measurement of the dc-ISHE confirms that the addition of the 50nm Al layer is sufficient to shortcut spin-orbit effect in the NM.
- [8] M. Sparks, *Ferromagnetic relaxation theory* (McGraw-Hill, New York, 1964)
- [9] O. G. Vendik, B. A. Kalinikos, and D. N. Chertoryzhskii, Sov. Phys. Solid State **19**, 222 (1977)
- [10] F. Guo, L. M. Belova, and R. D. McMichael, Phys. Rev. B **89**, 104422 (Mar 2014), <http://link.aps.org/doi/10.1103/PhysRevB.89.104422>
- [11] Patterning the NM into a coplanar double loop of size w , increases the FMI-sensitivity to $k \sim 1/w$.